Simulated Techno- Economic And Carbon Balance Analysis Of Off-Grid Solar Photovoltaic Power System For Remote Residential Apartment

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Abstract— **In this paper, techno- economic and carbon credit analysis of off-grid solar photovoltaic power system for remote residential apartment is presented. Technical analysis entails the determination of the PV system components parameter values while the economic analysis computation of the cost. Carbon balance analysis estimate the saving in CO2 emissions that is expected by the installation of the PV power system. The case study household is located in Uyo, Akwa Ibom State Nigeria and it has energy demand of 13204 Wh per day. The whole analysis were conducted using PVSyst software. The results showed that the system was designed for 5 % loss of load probability and 4 days power autonomy and it required 33 units PV array consisting of 130 Wp solar panels that generate a total of 4.3 kWp nominal power. Also, the system required 52 units of 100 Ah battery with a total of 49.9 kWh total energy storage capacity at 80 % depth of discharge (DoD). Again, the annual energy production was 6002 kWh /year, the solar fraction was 98.7 % and the performance ratio was 63.6 %. The unit energy cost was 238 Naira per kWh. The carbon balance results show that there is a saving of 54.576 tons of carbon due to the installation of the PV power system.**

Keywords— ***loss of load probability , CO2 emissions , techno- economic analysis, solar photovoltaic, carbon credit analysis, power system***

1. INTRODUCTION

As the effect of greenhouse emissions continues to manifest in diverse ways across the globe, the quest for clean energy sources becomes more urgent [1,2,3,4,5,6,7,8]. The national grid in most African nations are not accessible large percentage of the nations' population and this warrant the use of alternative energy source[9,10,11,12,13,14,15,16,17]. In most cases, the alternative source readily affordable in such nations are the fossil fuel-based energy generators [18,19, 20,21, 22,23, 24, 25, 26].

In any case, the solar photovoltaic (PV) energy generators are clean options which can minimize the emission of harmful gasses into the environment [27,28, 29,30, 31,32, 33,34, 35]. Hence, in this paper, the techno- economic analysis along with carbon balance analysis of an off-grid solar photovoltaic power system for remotely located residential apartment is presented. The technical analysis is meant to determine the component sizes for such power system [36,37,38,39,40], the economic analysis is meant to provide the life cycle cost along with the unit cost of energy generated from the system [41,42,43,44,45,46,47,48]. The carbon balance analysis is meant to estimate the saving in CO2 emissions that is expected by the installation of the PV power system [[49,50,51,52,53,54,55]. The analysis was done using the notable PVSyst simulation software [56,57,58,59,60,61].

2 METHODOLOGY

Techno-economic analysis is a combination of technical and economic analysis. Technical analysis entails the determination of the PV system components parameter values while the economic analysis computation of the cost of acquiring, installing and maintaining the PV system all through its lifetime and also to determine the unit cost of energy of the PV system. The technical analysis involves determination the target load demand, the solar radiation data of the operating location of the PV system, and determination of the PV system components parameter sizes. The case study load is for a residential apartment in Uyo, Akwa Ibom State with load demand profile given in Figure 1 while the screenshot of the hourly load distribution is given in Figure 2. The solar radiation data of the operating location of the PV system is given in Figure 3; it has geo-coordinates with of latitude of 5.05 and longitude of 7.9. The system has energy demand of 13204 Wh per day.

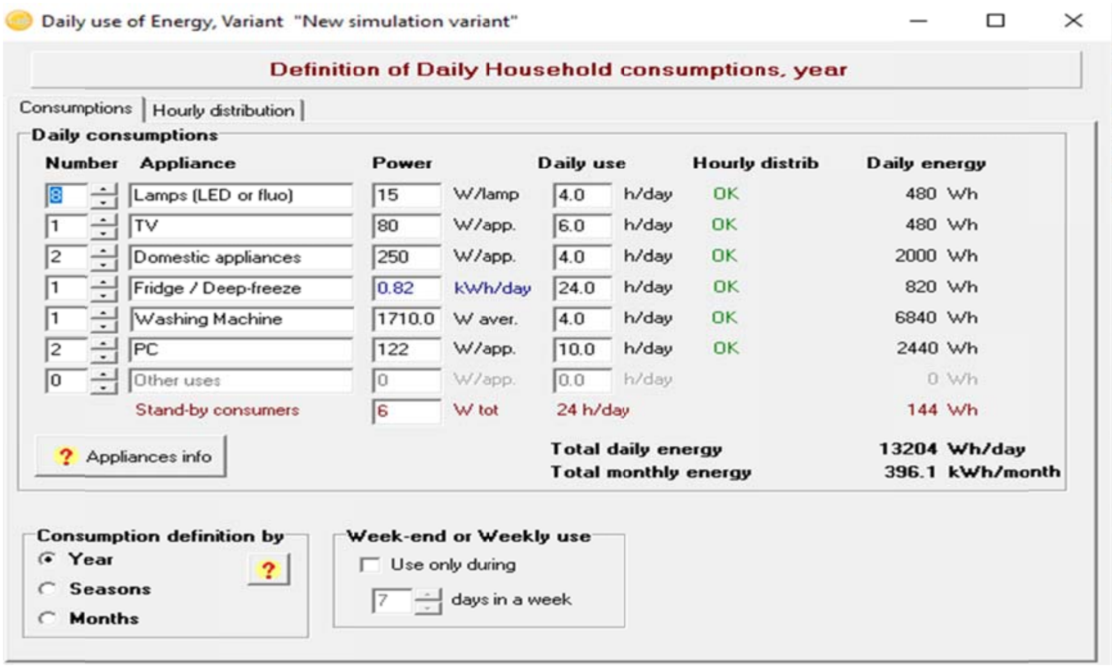

Figure 1 The load profile for the case study residential apartment in Uyo

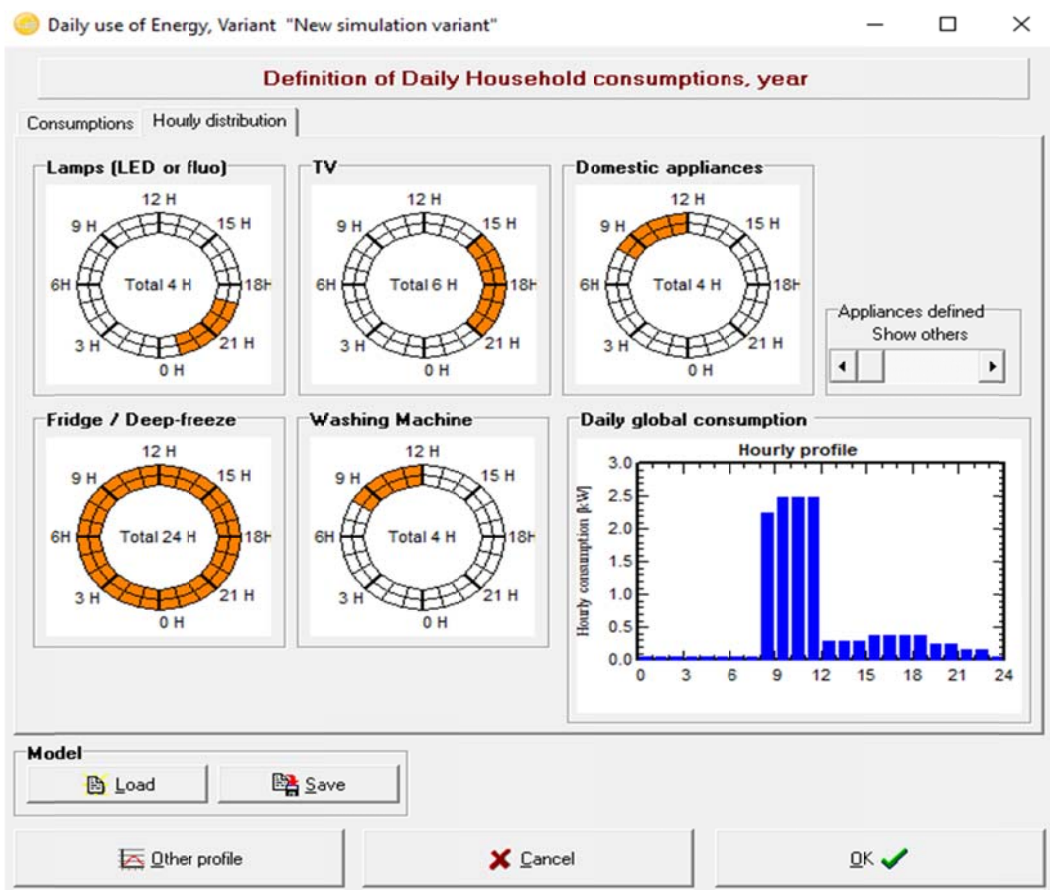

Figure 2 The screenshot of the hourly load distribution for the case study residential apartment in Uyo

	Global Irrad. kWh/m².mth	Diffuse kWh/m².mth	Temper. °C
January	171.4	53.6	25.4
February	156.5	55.2	25.8
March	164.9	68.8	25.7
April	152.7	68.1	25.8
May	146.3	67.6	25.6
June	129.3	63.3	24.8
July	119.4	66.0	24.1
August	116.9	68.2	23.9
September	118.2	68.1	24.1
October	132.4	67.3	24.4
November	145.2	58.5	24.7
December	164.0	53.0	24.7
Year	**1717.2**	**757.7**	**24.9**

Figure 3. The solar radiation data of the operating location of the PV system

2.1 Technical Analysis of the PV Power System

The optimal tilt angle (β_{opt}) of the PV module is determined as follows;

$$\beta_{\text{opt}} = 3.7 + 0.69\,|\text{Lat}| \quad (1)$$

where Lat denotes the latitude of the installation site.

The PV array output power (P_{pva}) is defined as :

$$P_{\text{pva}} = \frac{E_l}{f_d(\text{PSH})} \quad (2)$$

Where the parameters are PSH (peak sun hours), f_d (derating factors), E_l (daily electric load demand shown in Table 1).

The number of solar panel to be connected in series (N_{pvs}) is defined as;

$$N_{pvs} = \frac{V_{sys}}{V_{pv}} \quad (3)$$

Where the parameters are V_{sys} (the system line voltage), V_{pv} (nominal voltage of each of the PV module). Again, the PV module array output power (P_{pva}) is defined as;

$$N_{pvp} = \frac{P_{pva}}{N_{pvs}(P_{pv})} \quad (4)$$

Where the parameters are P_{pv} (power output of each solar panel) and N_{pvp} (number of PV module string in parallel). The required number of PV modules (N_{pvT}) is defined as;

$$N_{pvT} = N_{pvp}\,(N_{pvs}) \quad (5)$$

The battery bank capacity (C_{ba}),is defined as

$$C_{ba} = \frac{(E_l)\,n_a}{(\eta_{ba})(DOD_{max})(V_{sys})} \quad (6)$$

Where the parameters are $DOD_{\max}$ (maximum depth of discharge), η_{ba} (battery efficiency) and n_a (number of days of autonomy)

The total number of batteries (N_b) used is defined as;

$$N_b = \frac{C_{ba}}{C_b} \quad (7)$$

Where the parameters are N_{bs} (number of series connected batteries), N_{bp} (number of parallel connected battery strings) and V_b (nominal voltage of each battery). Then;

$$N_{bs} = \frac{V_{sys}}{V_b} \quad (8)$$

$$N_{bp} = \frac{N_b}{N_{bs}} \quad (9)$$

2.2 Economic and Carbon Balance Analysis of the PV Power System

Then, the total cost of the PV array, denoted as C_{pv} is given as;

$$C_{pv} = N_{pvT}(P_{pv})(UC_{pvwp}) \quad (10)$$

Where UC_{pvwp} is the unit cost of PV array per ratted watt. The installation cost (C_{inst}) is taken as 10% of the PV cost, hence,

$$C_{inst} = 0.1(C_{pv}) \quad (11)$$

Let A_{batcc} denote the charge controller rating in ampere and $UC_{batccPA}$ denote the unit cost per ampere of the charge controller , then, the cost of the battery charge controller denoted as C_{batcc} is defined as;

$$C_{batcc} = A_{batcc} (UC_{batccPA}) \quad (12)$$

The cost of the inverter, (C_{inv}) is defined as;

$$C_{inv} = Inv_w (UC_{invPw}) \quad (13)$$

Where the parameters are Inv_w (inverter power rating) and UC_{invPw} (inverter unit cost per watt).

The initial cost of battery bank $(CC_{bat})$is defined as

$$CC_{bat} = Bat_{Ah} (UC_{bat}) \quad (14)$$

Where the parameters are Bat_{Ah} (required Ah rating of battery bank) and UC_{bat} (unit cost of battery per Ah).

The battery bank lasts for 5 years while the system life cycle is, N = 25 years. Therefore, every five years the battery bank is replaced. If i denotes the inflation rate and d denotes the discount rate, the $CC_{bat(\mathrm{N})}$ is computed for n = 5, 10,15, and 20, hence;

$$CC_{bat(\mathrm{n})} = C_{bat} \left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{n}} \quad (15)$$

The initial yearly operation and maintenance cost denoted as $C_{M\&O}$ is estimated as 2 % of the PV cost, hence,

$$C_{M\&O} = 0.02(C_{pv}) \quad (16)$$

Let $C_{TM\&O}$ denote the yearly operation and maintenance cost which is computed for the lifetime of the system, where;

$$C_{TM\&O} = C_{M\&O} \left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right) \left(\frac{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{N}}}{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)}\right) \quad (17)$$

The solar power system life cycle cost denoted as LCC is given as;

$$LCC = C_{pv} + C_{batcc} + C_{bat(5)} + C_{bat(10)} + C_{bat(15)} + C_{bat(20)} + C_{inv} + C_{inst} + C_{TM\&O} \quad (18)$$

Let ALCC denoted the yearly life cycle cost, then;

$$ALCC = LCC \left(\frac{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{N}}}{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)}\right) \quad (19)$$

The unit cost (UC) of electrical energy in N/kWh is calculated as;

$$UC = \frac{ALCC}{365(\mathrm{E_l})} \quad (20)$$

The PVSyst uses the economic analysis data to estimate the Carbon Balance which is the saving in CO2 emissions that is expected by the installation of the PV power system.

3 RESULTS AND DISCUSSION

The system component setting for PV array and the charge controller are presented in Figure 4 while the setting for the battery bank is given in Figure 5. According to Figure 4, the system was designed for 5 % loss of load probability and 4 days power autonomy and it required 33 units PV array consisting of 130 Wp solar panels that generate a total of 4.3 kWp nominal power. Also, Figure 5 shows that the system required 52 units of 100 Ah battery with a total of 49.9 kWh total energy storage capacity at 80 % depth of discharge (DoD).

The summary of the main results of the PV standalone power system is given in Figure 6. According to Figure 6, the annual energy production is 6002 kWh /year and the performance ratio is 0.637 (that is 63.6 %). The unit energy cost is 238 Naira per kWh. The results on the system energy balance and solar fraction shown in Figure 7 shows that the solar fraction is 0.987 which means that the PV power system is able to supply about 98.7 % of the total energy demand of the load. The details of the economic analysis of the PV system is given in Figure 8 which reaffirms the 238 Naira per kWh unit energy cost.

The result of the carbon balance analysis of the PV system is shown in Figure 9 and Figure 10 shows some details of the results on the carbon balance analysis of the PV system. The carbon balance results show that there is a saving of 54.576 tons of carbon due to the installation of the PV power system.

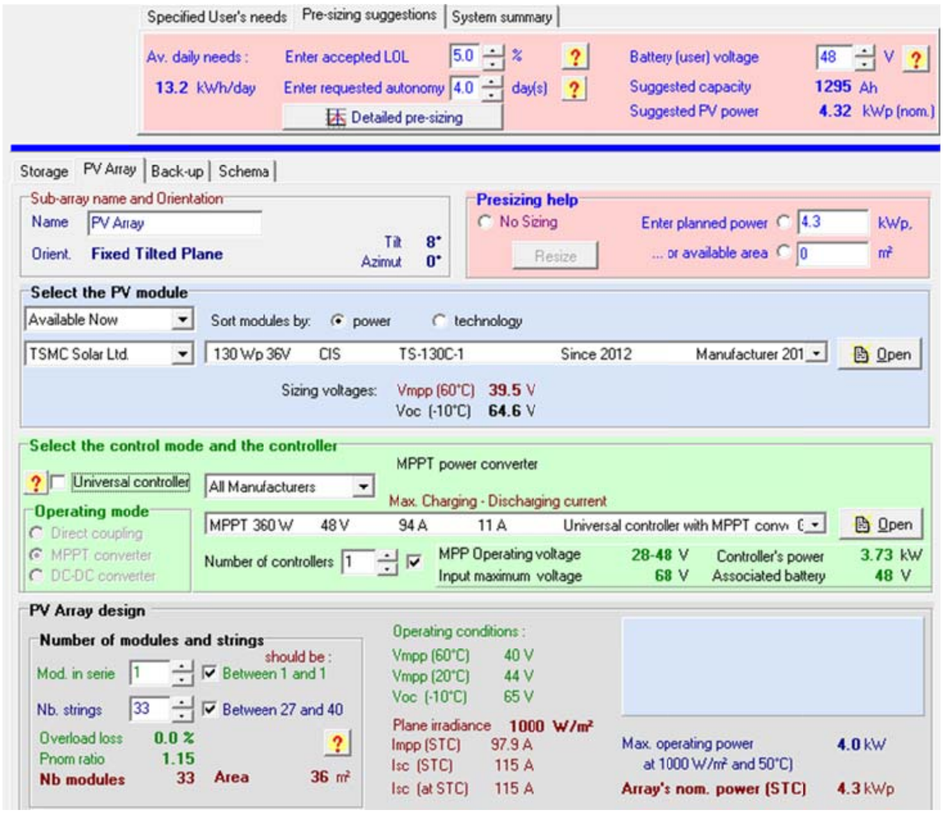

Figure 4 The system component setting for PV array and the charge controller

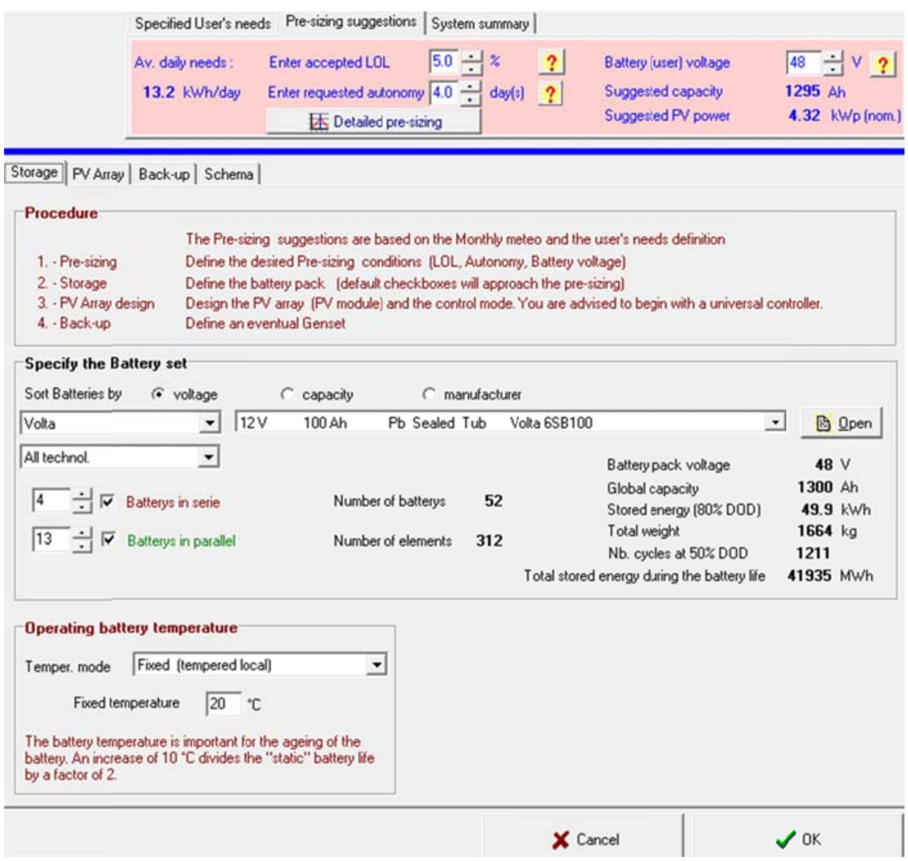

Figure 5 The system component setting for the battery bank

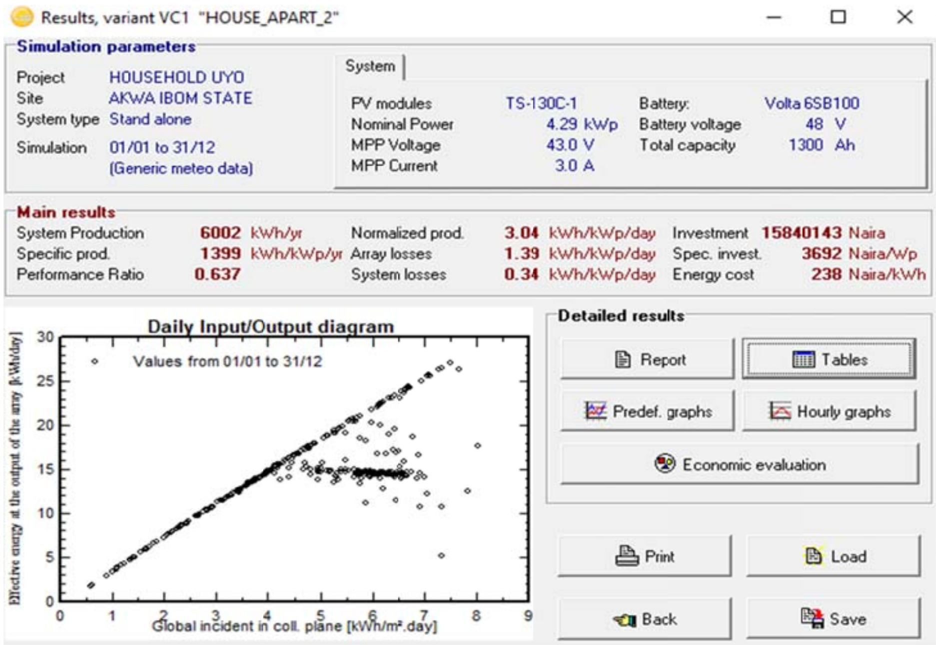

Figure 6 The summary of the main results of the PV standalone power system

Simulation variant : HOUSE_APART_1

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HOUSE_APART_1

Balances and main results

	GlobHor kWh/m²	GlobEff kWh/m²	E Avail kWh	EUnused kWh	E Miss kWh	E User kWh	E Load kWh	SolFrac
January	171.4	178.7	638.1	191.1	0.00	409.3	409.3	1.000
February	156.5	159.0	567.8	187.5	0.00	369.7	369.7	1.000
March	164.9	162.1	578.8	159.8	0.00	409.3	409.3	1.000
April	152.7	145.2	516.2	104.4	0.00	396.1	396.1	1.000
May	146.3	135.4	482.2	62.9	0.00	409.3	409.3	1.000
June	129.3	118.2	418.7	9.8	0.00	396.1	396.1	1.000
July	119.3	110.1	390.9	0.0	18.25	391.1	409.3	0.955
August	116.9	109.7	393.7	0.0	0.00	409.3	409.3	1.000
September	118.2	114.0	403.4	0.0	45.73	350.4	396.1	0.885
October	132.4	130.8	463.1	66.8	0.00	409.3	409.3	1.000
November	145.2	149.0	530.9	86.6	0.00	396.1	396.1	1.000
December	164.0	172.0	618.6	195.6	0.00	409.3	409.3	1.000
Year	1717.2	1684.2	6002.3	1064.6	63.98	4755.5	4819.5	0.987

Figure 7 The results on the system energy balance and solar fraction

PVSYST V6.70		07/08/22	Page 5/6

Stand Alone System: Economic evaluation

Project : **HOUSEHOLD UYO**
Simulation variant : **HOUSE_APART_2**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	8°	azimuth	0°
PV modules	Model	TS-130C-1	Pnom	130 Wp
PV Array	Nb. of modules	33	Pnom total	**4290 Wp**
Battery	Model	Volta 6SB100	Technology	Lead-acid, sealed, tubular
Battery Pack	Nb. of units	52	Voltage / Capacity	**48 V / 1300 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4820 kWh/year

Investment

PV modules (Pnom = 130 Wp)	33 units	300000 Naira / unit	9900000 Naira
Supports / Integration		3450 Naira / module	113850 Naira
Batteries (12 V / 100 Ah)	52 units	55000 Naira / unit	2860000 Naira
controller			500000 Naira
Settings, wiring, ...			50000 Naira
Substitution underworth			0 Naira
Gross investment (without taxes)			**13423850 Naira**

Financing

Gross investment (without taxes)		13423850 Naira
Taxes on investment (VAT)	Rate 18.0 %	2416293 Naira
Gross investment (including VAT)		15840143 Naira
Subsidies		0 Naira
Net investment (all taxes included)		**15840143 Naira**
Annuities	(Loan 5.0 % over 25 years)	1123897 Naira/year
Maintenance		0 Naira/year
insurance, annual taxes		0 Naira/year
Provision for battery replacement	(lifetime 9.0 years)	8380 Naira/year
Total yearly cost		**1132277 Naira/year**

Energy cost

Used solar energy	4756 kWh / year
Excess energy (battery full)	1064 kWh / year
Used energy cost	238 Naira / kWh

Figure 8 The details of the economic analysis of the PV system

PVSYST V6.70		07/08/22	Page 6/6

Stand Alone System: CO2 Balance

Project : **HOUSEHOLD UYO**
Simulation variant : **HOUSE_APART_2**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	8°	azimuth	0°
PV modules	Model	TS-130C-1	Pnom	130 Wp
PV Array	Nb. of modules	33	Pnom total	**4290 Wp**
Battery	Model	Volta 6SB100	Technology	Lead-acid, sealed, tubular
Battery Pack	Nb. of units	52	Voltage / Capacity	**48 V / 1300 Ah**
User's needs	Daily household consumers	Constant over the year	Global	4820 kWh/year

Produced Emissions	**Total:**	**8.23 tCO2**		
	Source:	Detailed calculation from table below		
Replaced Emissions	**Total:**	**72.4 tCO2**		
	System production:	6002.26 kWh/yr	Lifetime:	30 years
			Annual Degradation:	1.0 %
	Grid Lifecycle Emissions:	402 gCO2/kWh		
	Source:	IEA List	Country:	Nigeria
CO2 Emission Balance	**Total:**	**54.6 tCO2**		

System Lifecycle Emissions Details:

Item	Modules	Supports
LCE	1713 kgCO2/kWp	2.68 kgCO2/kg
Quantity	4.29 kWp	330 kg
Subtotal [kgCO2]	7348	885

Figure 9 The result of the carbon balance analysis of the PV system

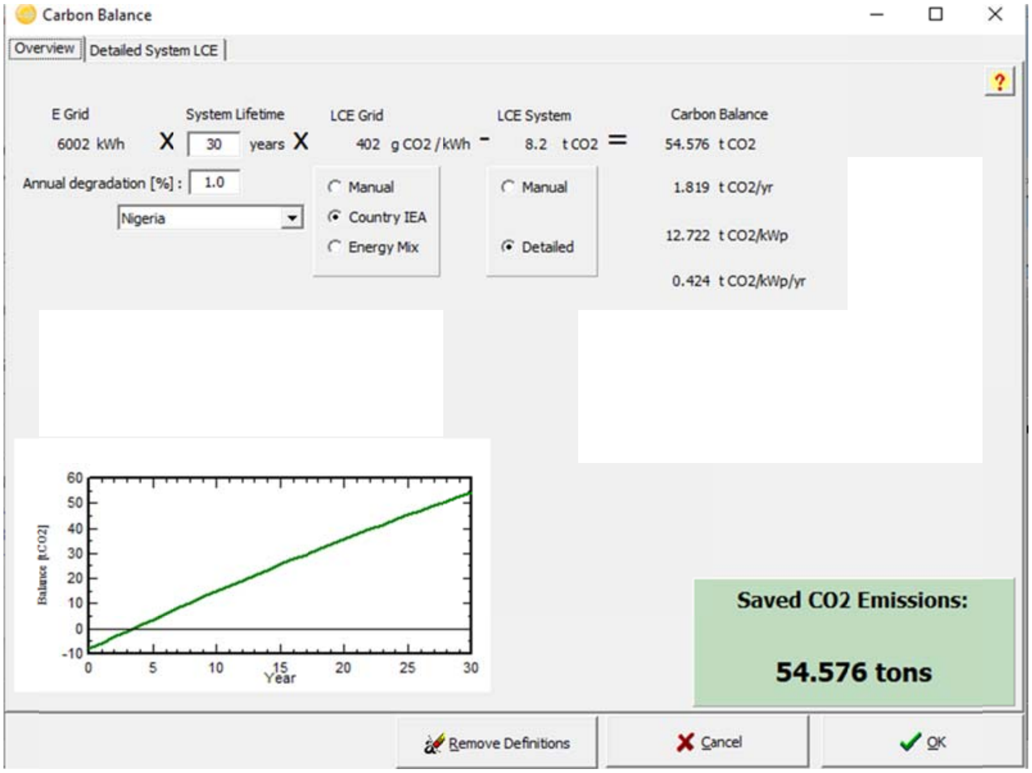

Figure 10 The details of results on the carbon balance analysis of the PV system

4 CONCLUSION

The technical, economic and carbon balance analysis of a PV solar power system for a household is presented. The mathematical expressions are presented and the actual analysis is performed using PVSyst software. The analysis yielded the PV module and battery requirements along with order system sizing parameters. The results included the total energy production, the solar fraction, the unit energy cost and the total carbon balance of the system along with other system losses and performance parameters.

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